X-ray Continuum Sources

Astrophysical origins of high-energy electromagnetic radiation

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General Outline

I. Introduction and the basics of electrodynamics

II. Continuous Radiative Processes

- Thermal Radiation
- Thomson & Compton/Inverse Compton Scattering
- Pair Creation and Annihilation
- Bremsstrahlung
- Cyclotron and Synchrotron radiation

III. Exotic Phenomena

- Radiation from Magnetic Compact Objects
  - - Magnetars
- Cosmic Background Radiation Effects

Introduction

- The observational information we obtain about our immediate surroundings (the solar system, the milky way galaxy, etc.), distant stars and galaxies, clusters of galaxies, and the far corners of the universe as visible light, radio waves, x-ray and γ-ray radiation; is primarily due to manifestations of the interaction among charged particles that are abundantly available as matter (or parts of matter) in and around astronomical objects of interest.

- We now know that an ever present microwave background radiation left over from the Big Bang era permeates the universe, making its interaction with charges and other radiation essential to our understanding of astrophysical phenomena.

Introduction II

- A surprising number of observations may be adequately described through the theory of Classical Electrodynamics and its associated language of charges, fields, and waves, which already embodies Einstein's theory and the principle of relativity.

- Yet for a thorough understanding of astrophysical phenomena, we need to rely on a more accurate description of nature through a highly successful description of electromagnetic interactions codified in the theory of Quantum Electrodynamics with its associated language of charged particles and quantized fields that behave as particles. This sophisticated theory combines Einstein's theory of relativity with the principles of quantum physics.

Introduction III

- Richard Feynman’s diagrammatic representation of quantum electrodynamics processes and calculations provides a convenient language for describing radiative processes in astrophysics. It is not necessary to know all the details of the theory to appreciate the utility of this mode of describing nature.

- One of the most important features of the theory of quantized fields is the creation and annihilation of particles under certain circumstances in accordance with the important conservation laws of nature.

- We shall utilize this diagrammatic method as a unified language for discussing radiative processes (such as Compton Scattering, Bremsstrahlung, Synchrotron radiation, etc.) all in the framework of interactions among charged particles (electrons, protons, etc.) and quantized field particles (photons)

- After a brief presentation of the basics of electrodynamics, we will consider radiative processes in some detail, and will end with the discussion of some exotic phenomena such as the behavior of matter and radiation near strong electromagnetic fields (magnetars).

Basics

- Electric (and possibly magnetic) charge is that locally conserved quantity which determines the strength of non-gravitational long-range interactions between particles

- Interactions with a charge can be described by local fields created by other charges

- ALL electromagnetic radiation comes from the far-field of accelerated charges

Electrodynamics

- Quantum electrodynamics
  - Maxwell's equations (for photon states)
  - Wave equation (Dirac for electron states)

$h \Diamond 0$:

- Classical electrodynamics
  - Maxwell's equations (for EM fields F)
  - Newton-Einstein with Lorentz force: $m\,\ddot{u} = q\,F \cdot u$

QED in a nutshell

$$\Box A^{\mu} = 4\pi e \bar{\psi} \gamma^{\mu} \psi \qquad \partial_{\mu} A^{\mu} = 0$$

`Gauge Condition'

$$(\gamma^{\mu}(p_{\mu} - e A_{\mu}) - m)\psi = 0$$

(Maxwell and Dirac Equations combined)

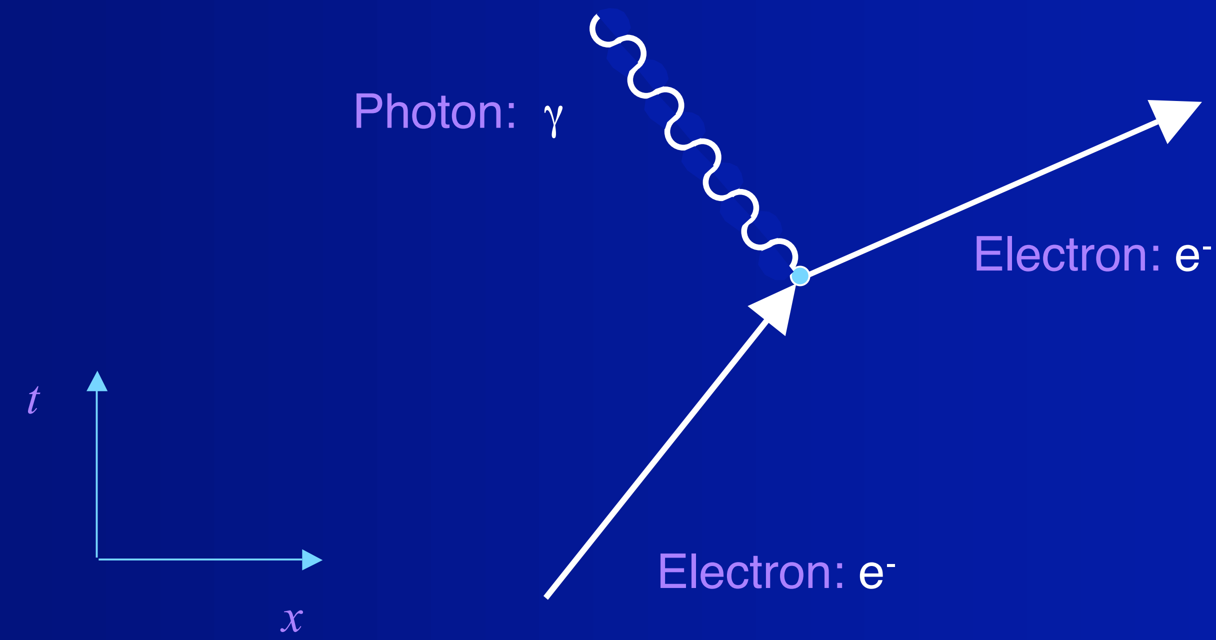
(units with $\hbar = 1$, $c = 1$)

A and ψ are the photon and electron fields. (Feynman: ψ represents both electron and positron states as the positive and negative energy components.)

This is a non-linear system. Because $\alpha = e^2 / \hbar c << 1$, and because of gauge symmetry, a perturbation 'renormalized' series in α works very accurately to explain processes involving only a few number of photon exchanges.

Making Photons I

Basic Feynman diagram:



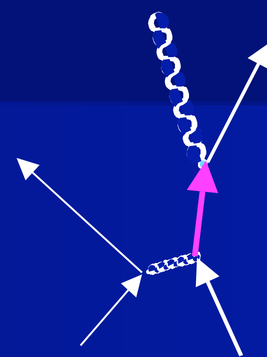
Lines and vertices corresponds to specific factors in a transition amplitude for the process

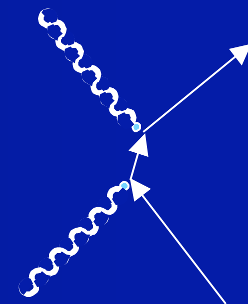
Making Photons II

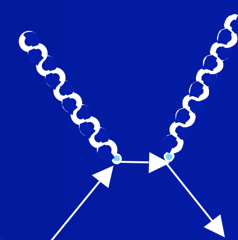
- Bound particles have quantized energies E_i. Transitions of charges from excited states to lower-energy bound states makes photons with energies peaked at $\Delta E = E^*_i - E_j$. X-rays and gamma rays possible from
  - Atomic transitions for tightly-bound electrons
  - Nuclear photo-transitions
  - Spin flip in strong B fields
  - Landau level changes in strong B fields
- "Unbound particles" have a "continuum" of possible energies; Acceleration of these can produce a continuum of photon energies.

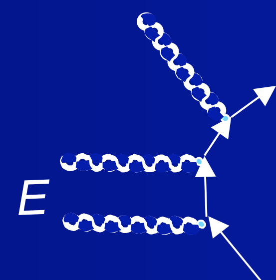
Making Photons in the "Continuum"

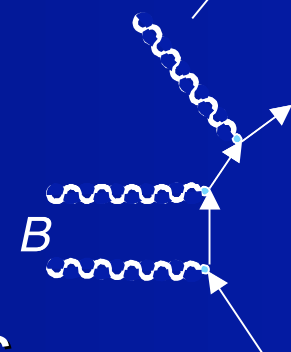
- Thermal emissions
- Compton Scattering &
  "Inverse" Compton Scattering
- Pair annihilation
- Bremsstrahlung
- Synchrotron Radiation
- Vacuum polarization effects

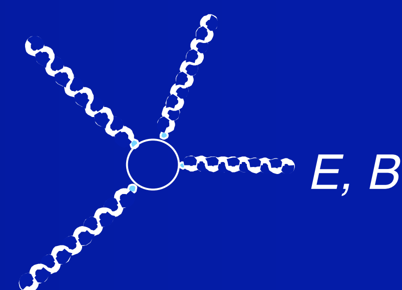








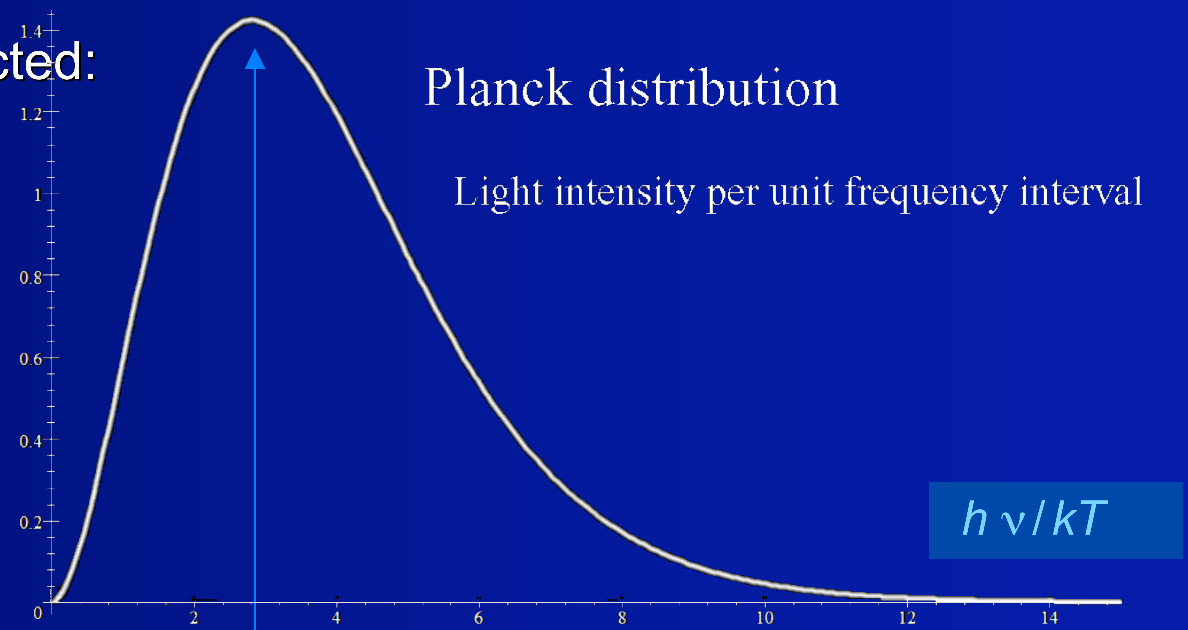




Thermal Emissions

- Thermal vibrations of matter (containing charges) makes radiation
- Max Planck predicted:

$$\frac{dI}{d\nu} = \frac{8\pi}{c^2}\,\frac{h\nu^3}{e^{h\nu/kT}-1}$$



Intensity peaks at

$$h\nu = 2.4313 \text{ eV } T_4$$

1 keV X-rays: ◊ $T \sim 4$ million degrees Kelvin

X-rays: 10^6 to 10^9K

γ-rays: $>10^9$K

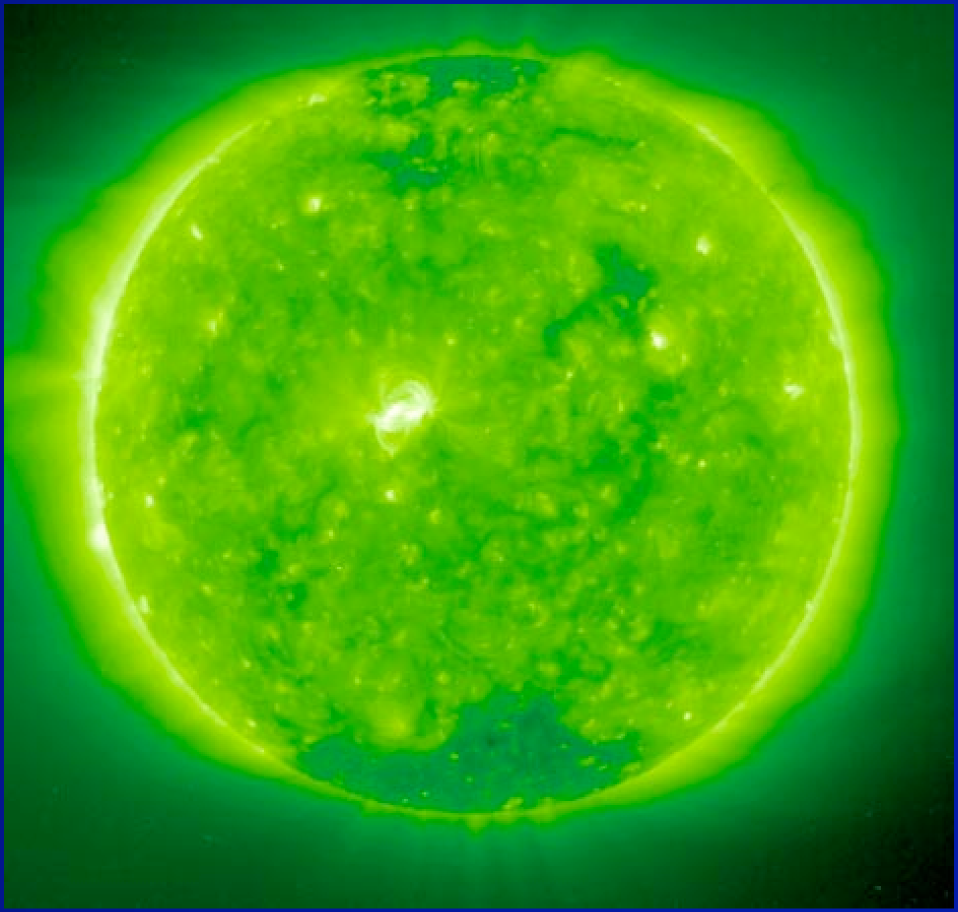
X-ray image of our Sun

Soft: Thermal bremsstrahlung

($k\,T \sim 40$ keV)

Hard: Non-thermal (power-law) bremsstrahlung; fluctuates with flares

Electrons, accelerated from surface by turbulent magnetic plasma, hit ions above



Radiation from accelerated charges

Dipole radiation power, non-relativistic :

$$dP/d\Omega = q^2|a|^2\sin^2\theta\,/(4\pi\, c^3)$$

Electric field polarized in the plane of *a* and propagation vector; power strongest in direction perpendicular to acceleration.

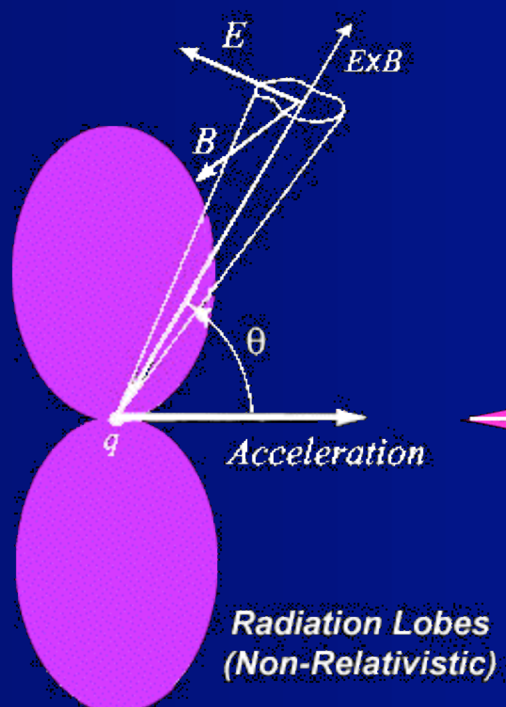
Over all angles,

$$P = (2/3)\, q^2|a|^2\,/c^3$$

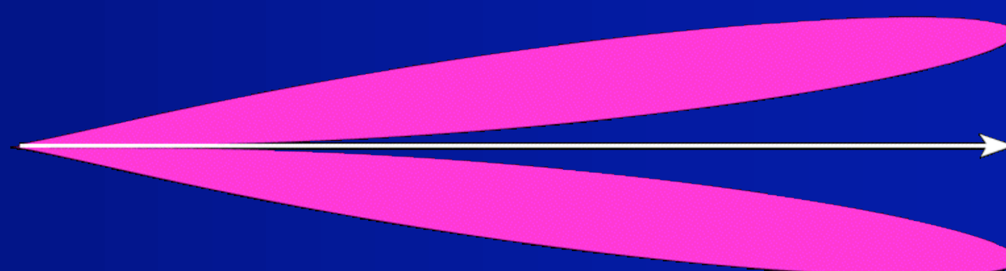
(Larmor's Formula)

Dipole radiation from accelerating charges

Non-Relativistic

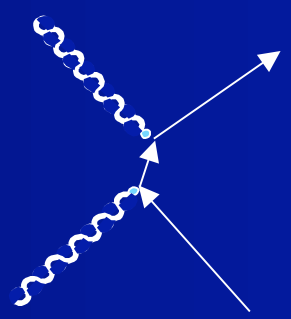


Relativistic



Photon-Electron Scattering

- This process is often called Compton scattering (Inverse Compton Scattering) when kinematical and dynamical quantum effects are significant, and Thomson scattering when the classical approximation yields accurate results.



- In this particular case, it is instructive to go through the details of calculations to see how the classical and quantum descriptions differ. We start with Thomson Scattering and find the scattering cross section.

Thomson Scattering

- Plane wave of monochromatic electromagnetic radiation incident on a free electron (charge e, mass m)
- Consider an incident wave of propagation vector $\vec{k}_0$ and polarization vector $\vec{\epsilon}_0$

$$\vec{E}(\vec{r},t)=\vec{\epsilon}_0 E_0 e^{i\vec{k}_0 . \vec{r}-i\omega t}$$

- The electron will accelerate in response to the oscillating electric field of the incident radiation

$$m\dot{\vec{v}}=e\vec{E}(\vec{r},t)$$

Thomson Scattering

$$\dot{\vec{v}} = \vec{\epsilon}_0 \frac{e E_0}{m} e^{i \vec{k}_0 . \vec{r} - i \omega t}$$

- The instantaneous power radiated in a polarization state $\vec{\epsilon}$ (which could be complex, e.g., circular polarization) by a particle of charge "e" in non-relativistic motion is (the average is performed over one cycle):

$$\frac{dP}{d\Omega} = \frac{e^2}{4\pi c^3} |\vec{\epsilon} \cdot \dot{\vec{v}}|^2$$

$$\langle \frac{dP}{d\Omega} \rangle = \frac{c}{8\pi} |E_0|^2 (\frac{e^2}{m c^2})^2 |\vec{\epsilon} \cdot \vec{\epsilon}_0|^2$$

Thomson Scattering

- This process can be viewed simply as a scattering process with a scattering cross section given by

$$\frac{d\sigma}{d\Omega} = \frac{Energy\ radiated / unit\ time / unit\ solid\ angle}{Incident\ energy\ flux\,(energy / unit\ area / unit\ time)}$$

$$\frac{d\sigma}{d\Omega} = \left(\frac{e^2}{mc^2}\right)^2 |\vec{\epsilon}\cdot\vec{\epsilon}_0|^2$$

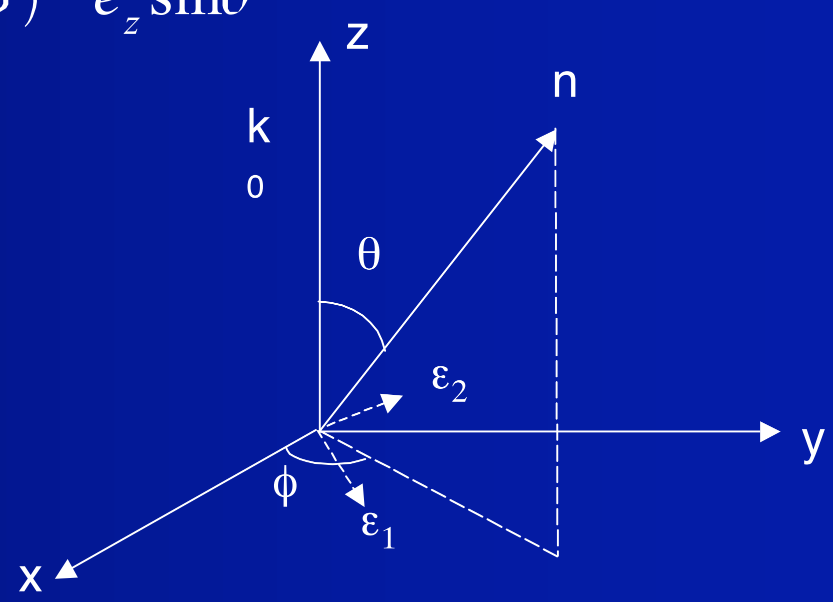
- The above formula gives the contribution to differential scattering cross section from a particular initial state of polarization into a definite final polarization state.

Thomson Scattering

- In the classical domain, each polarization state contributes separately (incoherently) to the cross section, and when unpolarized incident waves are considered the average of those individual contributions to the cross section are taken.

$$\vec{\epsilon}_1 = \cos\theta\,(\vec{e}_x \cos\phi + \vec{e}_y \sin\phi) - \vec{e}_z \sin\theta$$

$$\vec{\epsilon}_2 = -\vec{e}_x \sin\phi + \vec{e}_y \cos\phi$$



$\vec{\epsilon}_1$ is in the plane of n & k_0 and

Perpendicular to n.

$\vec{\epsilon}_2$ is perpendicular to both

$\vec{\epsilon}_1$ & n.

Thomson Scattering

- If the incident wave is polarized along the x-axis, after summing over the final polarization states, one obtains:

$$For\ \vec{\epsilon}_0 = \vec{e}_x$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\vec{e}_x} = \left(\frac{e^2}{m c^2}\right)^2 |\vec{\epsilon}_1 . \vec{\epsilon}_0|^2 + \left(\frac{e^2}{m c^2}\right)^2 |\vec{\epsilon}_2 . \vec{\epsilon}_0|^2$$

$$= \left(\frac{e^2}{m c^2}\right)^2 \left[(\cos\theta)^2 (\cos\phi)^2 + (\sin\phi)^2\right]$$

Thomson Scattering

- If the initial polarization of the incident wave is along the y-axis, the following cross section is obtained.

$$For\ \vec{\epsilon}_0 = \vec{e}_y$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\vec{e}_y} = \left(\frac{e^2}{mc^2}\right)^2 \left[(\cos\theta)^2 (\sin\phi)^2 + (\cos\phi)^2\right]$$

- For unpolarized incident waves, the average of these two differential cross sections should be calculated.

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left[\left(\frac{d\sigma}{d\Omega}\right)_{\vec{e}_x} + \left(\frac{d\sigma}{d\Omega}\right)_{\vec{e}_y}\right] = \left(\frac{e^2}{mc^2}\right)^2 \frac{1}{2}\left[1 + (\cos\theta)^2\right]$$

Compton Scattering

- Thomson formula for scattering of radiation by a free charged particle is appropriate for the scattering of x-rays from electrons or gamma rays by protons. The total cross section is

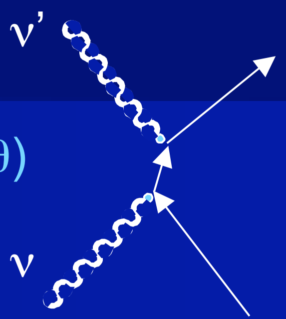
$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{mc^2}\right)^2 \quad with\ \sigma_T = 0.665 \times 10^{-24}\ cm^2\ for\ electrons$$

$$\frac{e^2}{mc^2} = 2.82 \times 10^{-13}\ cm\ is\ called\ the\ classical\ electron\ radius$$

- When the incident radiation is of low frequency, its momentum can be ignored, but when the recoil of the charged particle is not ignored, relativistic kinematics shows that the ratio of the outgoing to the incident wave numbers is given by

$$\frac{k'}{k} = \left[1 + \frac{\hbar\omega}{mc^2}(1 - \cos\theta)\right]^{-1} \quad with\ \theta \in the\ lab\ frame.$$

Photon-Electron Scattering



- Compton Scattering $\nu' / \nu = 1 + (h\nu / mc^2)\,(1 - \cos\theta)$

Relativistic expression for cross section:
Klein-Nishina formula:

$$\frac{d\sigma}{d\Omega} = \frac{e^4}{2\,m^2\,c^4}\left[\frac{\nu'}{\nu}\right]^2\left[\frac{\nu}{\nu'} + \frac{\nu'}{\nu} - \sin^2\theta\right]$$

(Incident electron at rest; averaged over photon polarization)

When $h\nu / c \ll mc$ (photon 'kick' negligible): Thomson scattering:

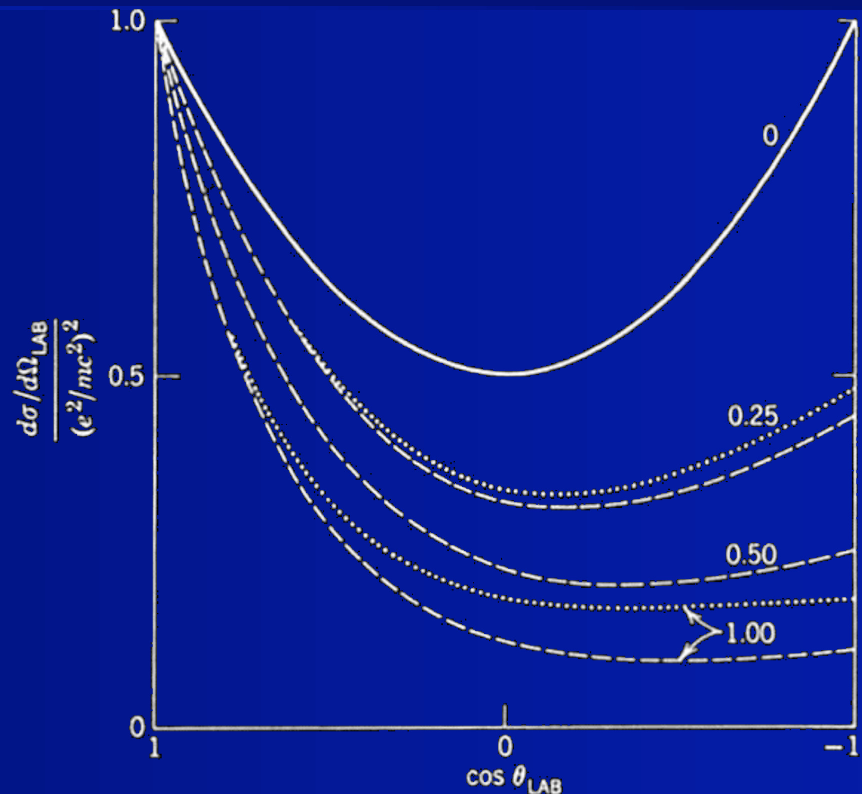
$$\frac{d\sigma_T}{d\Omega} = \frac{e^4}{2\,m^2\,c^4}\left[1 + \cos^2\theta\right]$$

- "Inverse" Compton Scattering: Moving electron scattered by light

"Comptonized photons": Light rescattered in a plasma

Thomson/Compton Scattering

Differential cross section for the classical (Thomson) and quantum-mechanical (Compton) photon-electron scattering.



Differential scattering cross section of unpolarized radiation by a point charged particle initially at rest in the laboratory. The solid curve is the classical Thomson result. The dashed curves are the quantum-mechanical results for a spinless particle, with the numbers giving the values of $\hbar\omega/mc^2$. For $\hbar\omega/mc^2 = 0.25$, 1.0 the dotted curves show the results for spin $\frac{1}{2}$ point particles (electrons).

From Jackson, 2nd Ed.

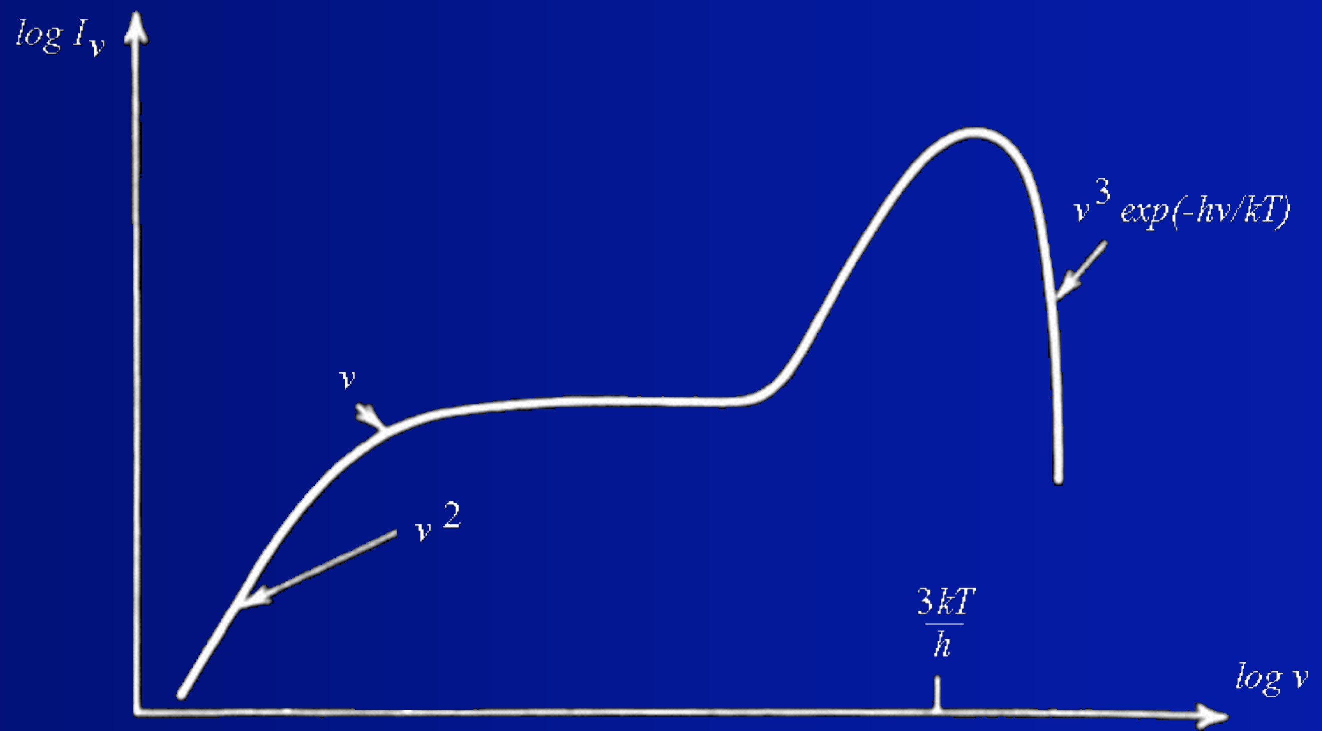
Inverse Compton Scattering

- Comptonization: If the evolution of the spectrum of the source is determined through Compton scattering primarily ◊ plasma must be rarefied so that other radiation processes such as Bremsstrahlung do not add photons to the system

- Whenever a moving electron has sufficient kinetic energy compared to the photon, net energy may be transferred from the electron to the photon, hence, *Inverse Compton Scattering*.

- Converts a low-energy photon to a high-energy photon by a factor of γ^2 !

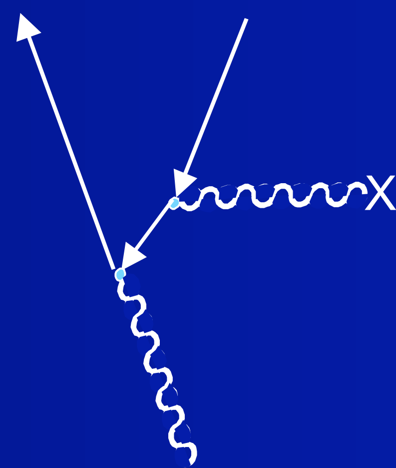
Inverse Compton Scattering



Spectrum from a thermal, non-relativistic medium characterized by free-free emission and absorption by saturated inverse Compton scattering. At low frequencies, the spectrum is blackbody, then becomes a modified blackbody, and, at high frequencies, we see a Wien spectrum.

Pair Creation and Annihilation

- ν $\gamma + X \Diamond e^+ + e^-$
- ν $e^+ + e^- \Diamond \gamma + \gamma$



Examples:

Pair creation from matter exposed to gamma rays

Pair creation in strong electric and magnetic fields

Pair creation near horizon of small black holes

Pair Creation and Annihilation

- Ultrahigh energy photons ($E_2 > 10^8$ eV) in collisions with microwave background radiation (6×10^{-4} eV), Starlight (2 eV), and X-rays (10^3 eV) produce electron-positron pairs

- In ultrarelativistic limit:

  $\sigma = (\pi r_e^2 m_e^2 c^4/E_1E_2)[2 \ln (2\omega/m_ec^2) - 1]$, with $\omega=(E_1E_2)^{1/2}$

- In the classical regime for $\omega \lozenge m_ec^2$:

  $\sigma \lozenge (\pi r_e^2) [1 - (m_e^2 c^4/ \omega^2)]^{1/2}$

Pair Creation and Annihilation

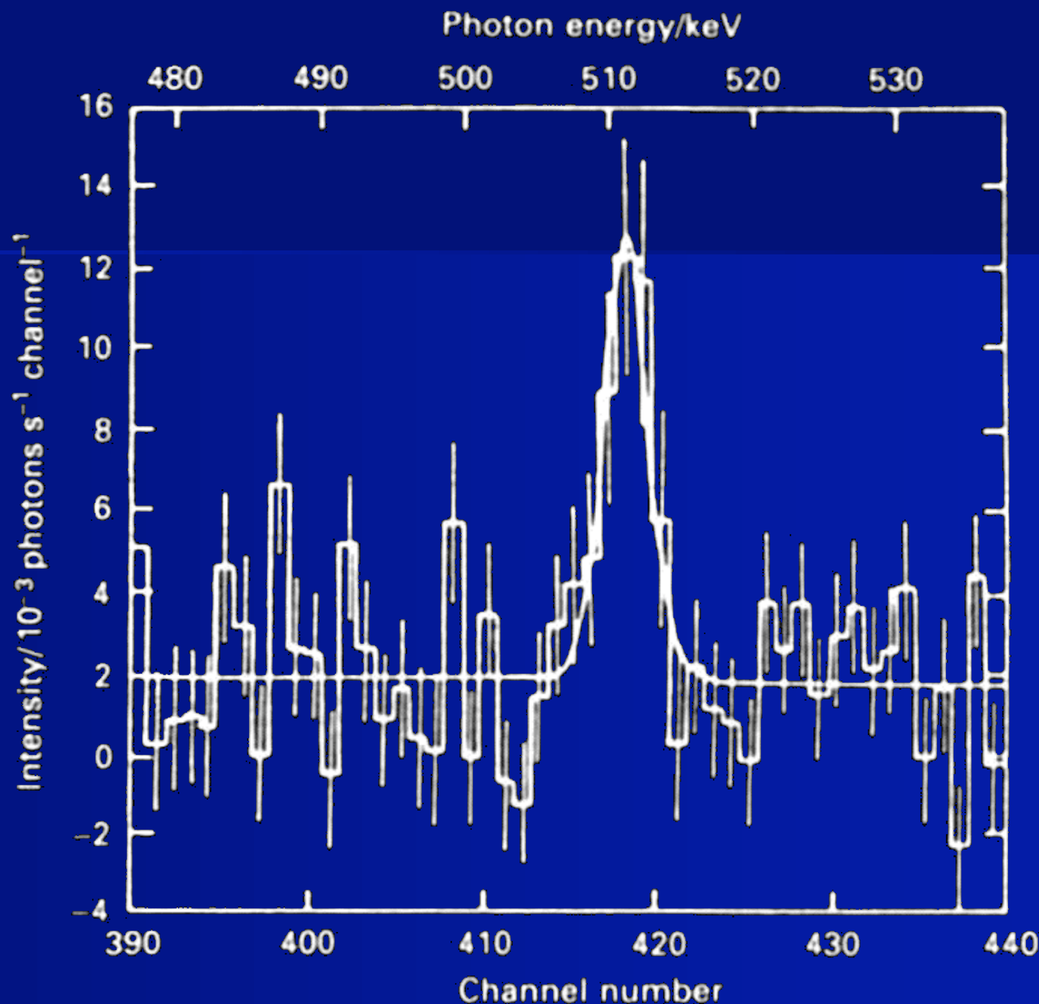
- Energy loss mechanism for electrons through the annihilation process
- Positively charged pions created in collisions of cosmic ray protons and nuclei are sources of positrons, as well as the decay of long-lived radioactive isotopes created by explosive nucleosynthesis in supernova explosions (β^+ decay of ^{26}Al with a mean half-life of 1.1 x 10^6 years)
- In the extreme relativistic limit:

  $\sigma = (\pi r_e^2/ \gamma) [\ln 2\gamma - 1]$

- For thermal electrons and positrons one gets:

  σ ◊ $(\pi r_e^2) / (v/c)$

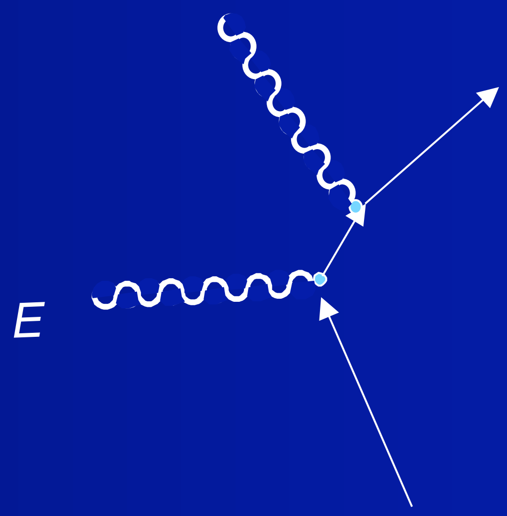
Observation of Pair Annihilation



HEAO-3 observations of the 0.511 MeV electron–positron annihilation line from the general direction of the Galactic Centre. The observations were made in autumn 1979. (From G. R. Riegler, J. C. Ling, W. A. Mahoney, W. A. Wheaton, J. B. Willett, A. S. Jacobson and T. A. Prince (1981). *Astrophys. J. Lett.*, **248**, 113.)

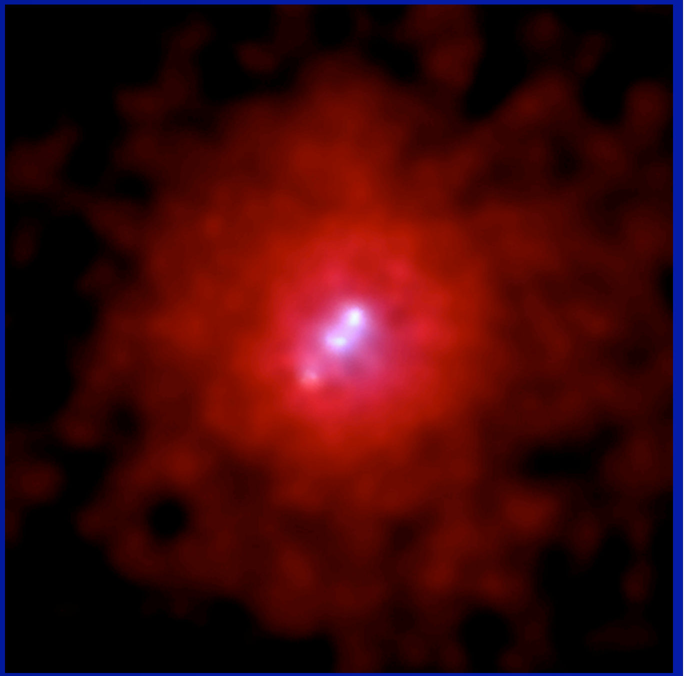
Bremsstrahlung

'Braking' radiation from charged particles deflected by an impulse from another charge. Dominant mode of energy loss for relativistic electrons in a hot plasma.



Bremsstrahlung Observed

3c295 galactic cluster in X-ray showing thermal bremsstrahlung emission in the center

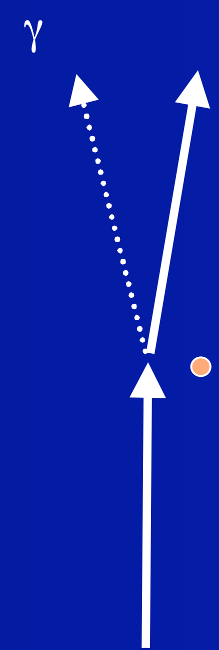


Note: Earth's aurora produced by bremsstrahlung!

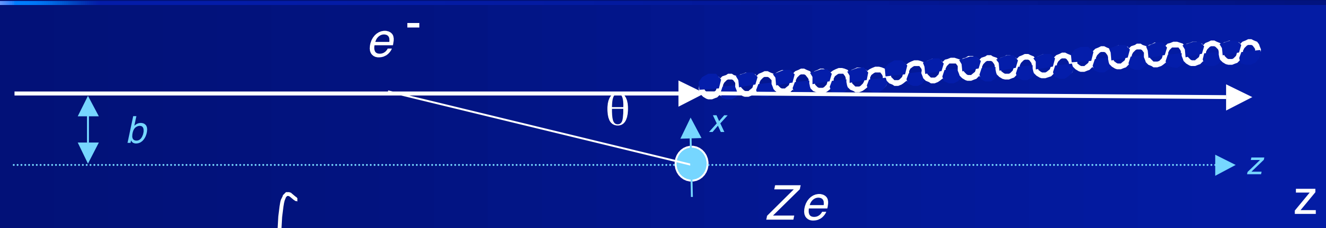
Bremsstrahlung Calculation

Strategy:

- 1. Find power spectrum from single encounter of electron and ion with given impact parameter
- 2. Integrate over all possible impact parameters
- 3. Integrate over distribution of electron velocities (e.g. thermal)



Bremsstrahlung Energy Loss



$$\text{Impulse} = \int F_x \, dt$$

$$= \int (Ze^2 \sin\theta / r^2)\, dz / v = \int_{-\infty}^{\infty} (Ze^2 b/v)\ (b^2 + z^2)^{-3/2} dz = 2Ze^2/bv$$

Electron kinetic energy loss

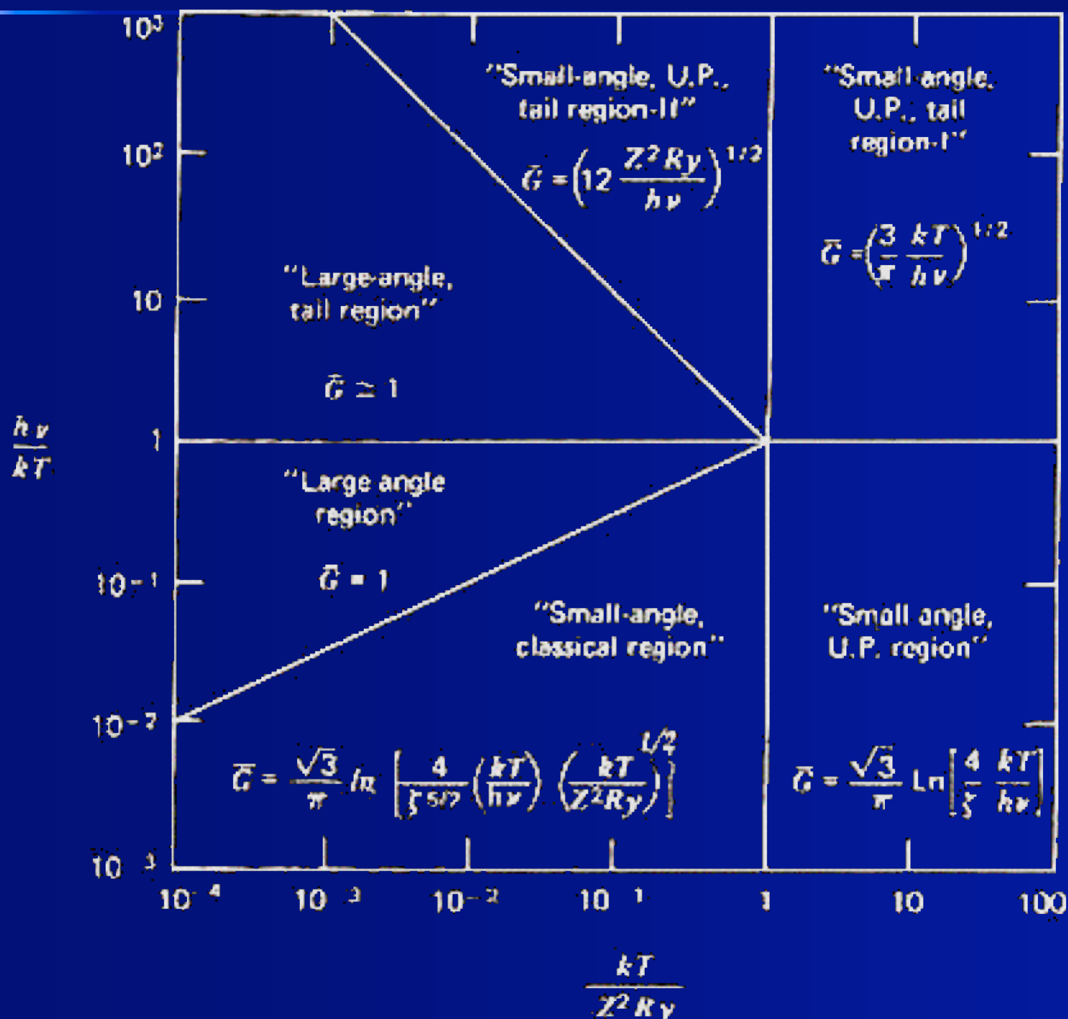
$$E = p^2/(2m_e) = 2\,(Ze^2)^2 / (m_e\, b^2\, v^2)$$

Sum over many electrons (with range of impact parameters *b*):

$$\delta E / \delta z = N_e \int 2\pi b\, db\, E = 4\pi N_e((k\,Z\,e^2)^2/(m_e v^2))\ \ln\,(b_{max}/b_{min})$$

With a full quantum theory calculation, the log factor becomes the ‘Gaunt factor’.

Bremsstrahlung Gaunt Factor



Approximate analytic formulae for $\langle g_{ff} \rangle$

From Rybicki & Lightman Fig 5.2 (corrected) -- originally from Novikov and Thorne (1973)

Bremsstrahlung Radiation

Relativistic Electrons

Use dipole radiation formula for the electron in its rest frame, kicked by a ion rapidly passing by, causing acceleration of the electron given by:

$$a'_x = eE_x/m_e = (Ze^2/\, m_e)\ b/\,(b^2+(\gamma vt)^2)^{3/2}$$

so

$$a'_z = eE_z/m_e = (Ze^2/\, m_e)\ \gamma v t\,/\,(b^2+(\gamma vt)^2)^{3/2}$$

Now the relativistic power radiated in the frame (S') of the electron is the same as that in the frame of the ion, because the energy differences and time intervals both transform with a gamma factor:

$$dE\,/dt = dE\,'/dt\,'$$

Lorentz transforming the acceleration from the frame of the electron to that of the ion gives

$$a'^{\,2} = \gamma^4\,(\,a^2 + \gamma^2\,(v \cdot a\,/\,c)^2)$$

Bremsstrahlung Spectrum

The electromagnetic pulse emitted from a jiggled charge gives a spectrum of frequencies.

The power per unit frequency is

$$\frac{dP}{d\omega} = \frac{2e^2}{3c^3} \, | a'(\omega) |^2$$

$$\frac{dP}{d\nu} = \frac{4\pi e^2}{3c^3} \gamma^4 (a^2 + \gamma^2 (v \cdot a / c)^2)$$

$$I(\omega) \lozenge [(1/\gamma^2) K_0^2(\omega b/\gamma v) + K_1^2 (\omega b/\gamma v)],$$

with K_0 and K_1, modified Bessel functions

Bremsstrahlung Spectrum

- At High frequencies, exponential cut-off:

  $I(\omega) \lozenge \exp(-2\omega b/\gamma v)$

- At low frequencies, flat:

  $I(\omega) \lozenge$ constant

- For a quantum treatment, note that the emitted photon energy is limited to the maximum electron kinetic energy (Bethe-Heitler treatment)

Astrophysical Magnetic Fields

Galaxy	10^{-6}	Gauss
Molecular cloud	10^{-3}	Gauss
Earth	1	Gauss
Massive star	10^{2}	Gauss
Sun spot	10^{3}	Gauss
Jupiter	10^{3}	Gauss
White dwarf	10^{6}	Gauss
Neutron star	10^{12}	Gauss
Magnetar	10^{14}	Gauss

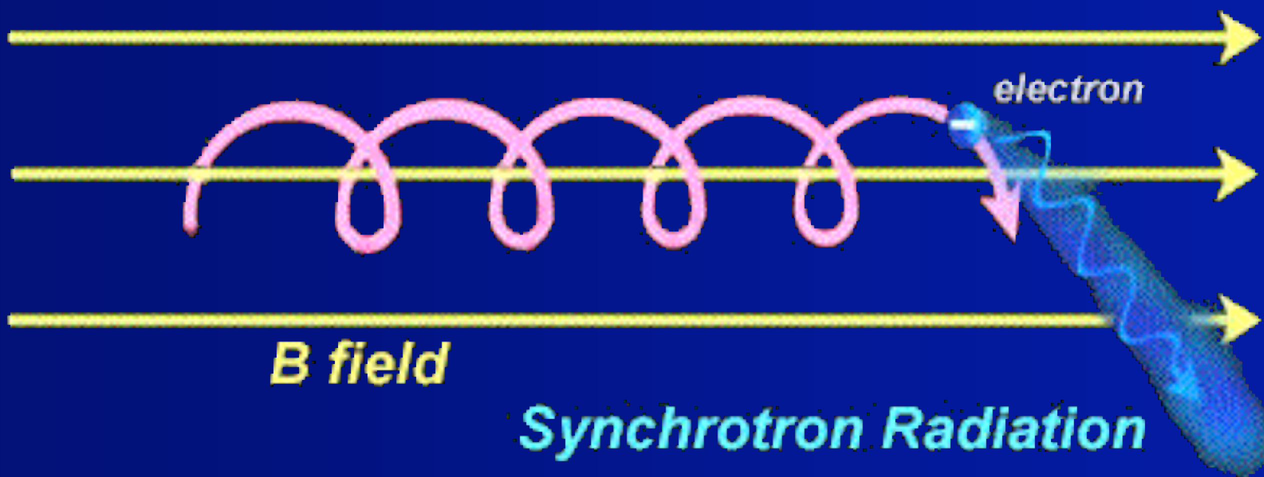
(B Field next to proton ~ 10^{16} Gauss)

(1 Tesla = 10^{4} Gauss)

Origin of Astrophysical Magnetic Fields

- Magnetic fields created by currents and by changing electric fields.
  - Dynamo effect: Differential motion of charged matter can create currents.
  - Magnetic field can sustain currents (Faraday's Law).

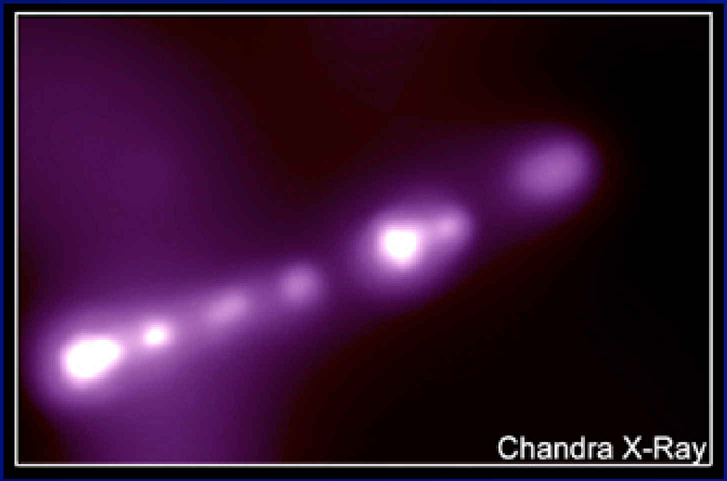
Radiation from charges accelerated in a magnetic field



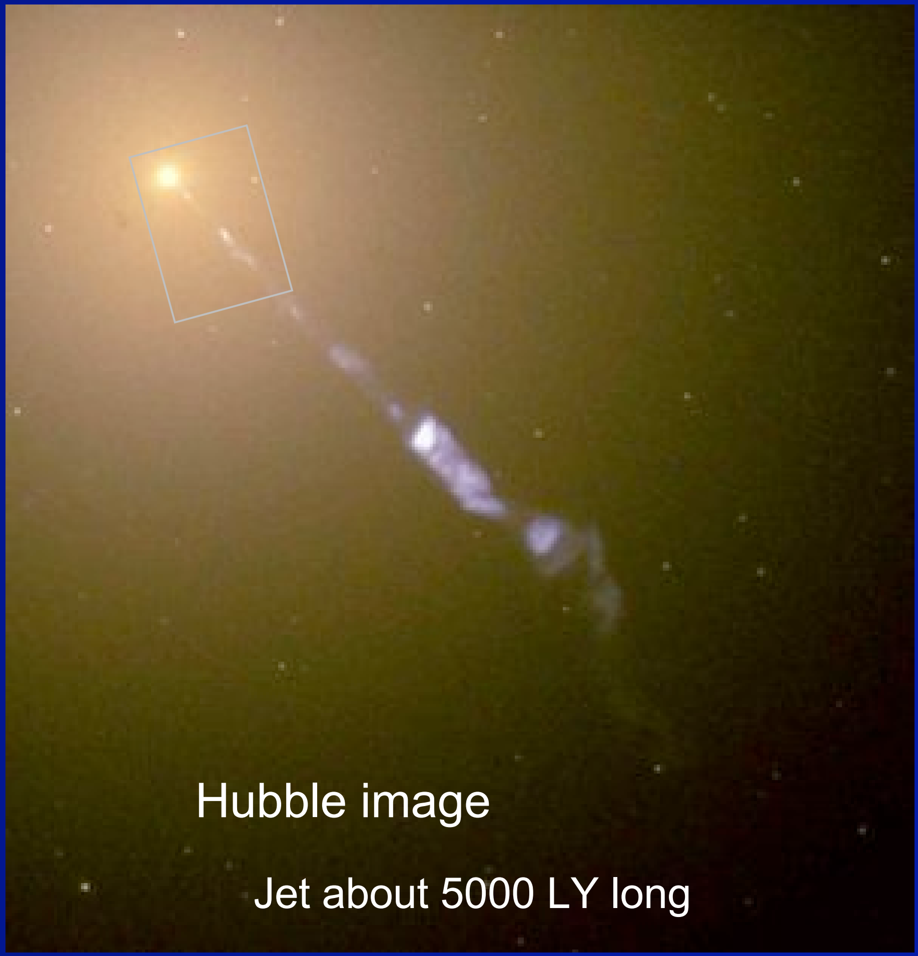
(Non-relativistic: Cyclotron radiation)

Synchrotron Radiation Examples

Image of M87
Synchrotron X-ray
Radiation Glow
and Jet



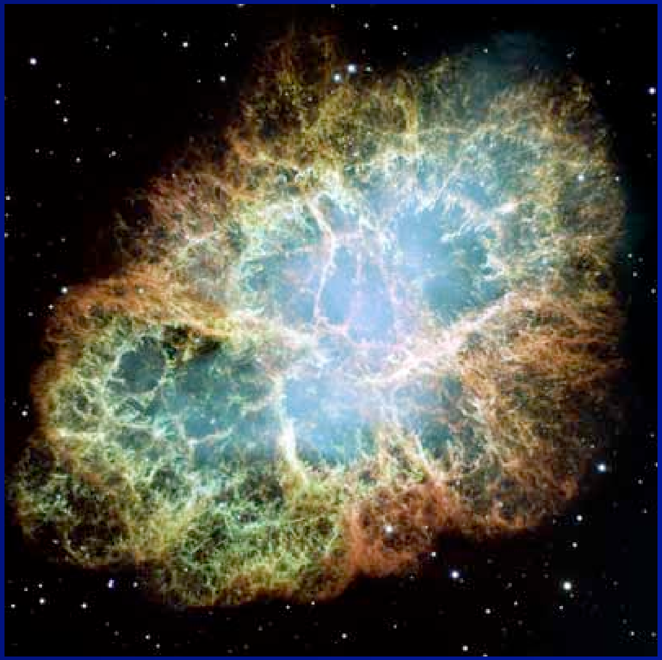
(50 MLy from us in Vergo)



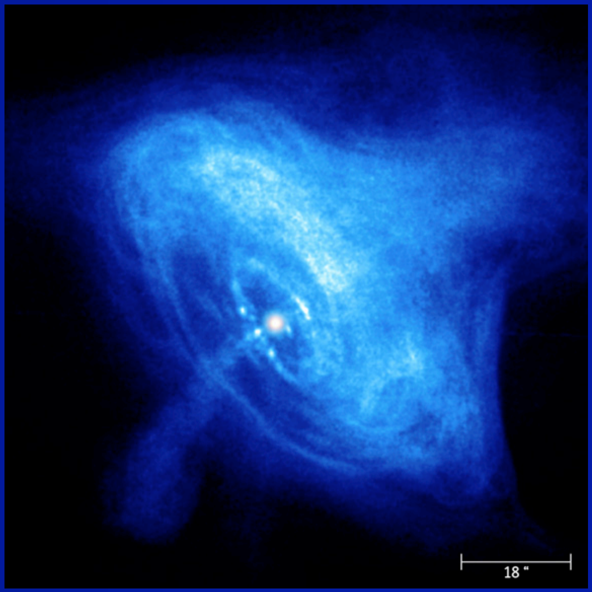
Synchrotron radiation-lit nebulae

Crab Nebula

Supernova in 1054 AD

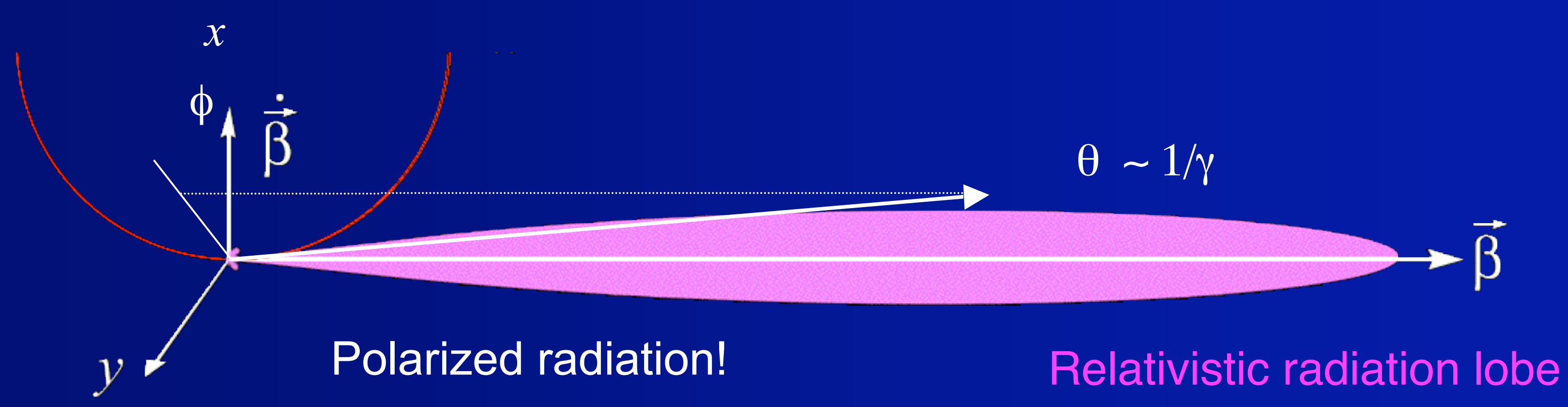


X-ray close-up of Crab pulsar



Synchrotron Radiation Theory

Radiation by magnetic deflection of relativistic particles



Synchrotron Radiation Theory II

Power radiated per unit solid angle:

$$\frac{dP}{d\Omega} = \frac{k\,e^2}{4\pi c^3} \frac{\dot{\vec{\beta}}^{\,2}}{(1-\beta\cos\theta)^3} \left[1 - \frac{\sin^2\theta \cos^2\phi}{\gamma^2(1-\beta\cos\theta)^2} \right]$$

(Jackson)

$\beta = v / c$

$\gamma = 1 / \sqrt{1 - v^2 / c^2}$

$\dot{\vec{\beta}}^2 = \omega^2 \beta^2$

Larmor 'gyration' frequency

$\omega_L = e\,B / m_e c = 2.8 \text{ MHz } B_{1G}$

$\omega_B = \gamma^{-1}\omega_L$

Power radiated over all angles:

$$P = (2 / 3) (k\,e^2 / c^3)\, \omega_L^2\, \beta^2\, \gamma^2$$

Synchrotron Radiation Theory III

Power radiated per unit solid angle per unit frequency interval:

Low frequency end:

$$dP / d\Omega \, d\nu \;\; / \;\; \nu^{2/3}$$

High frequency end:

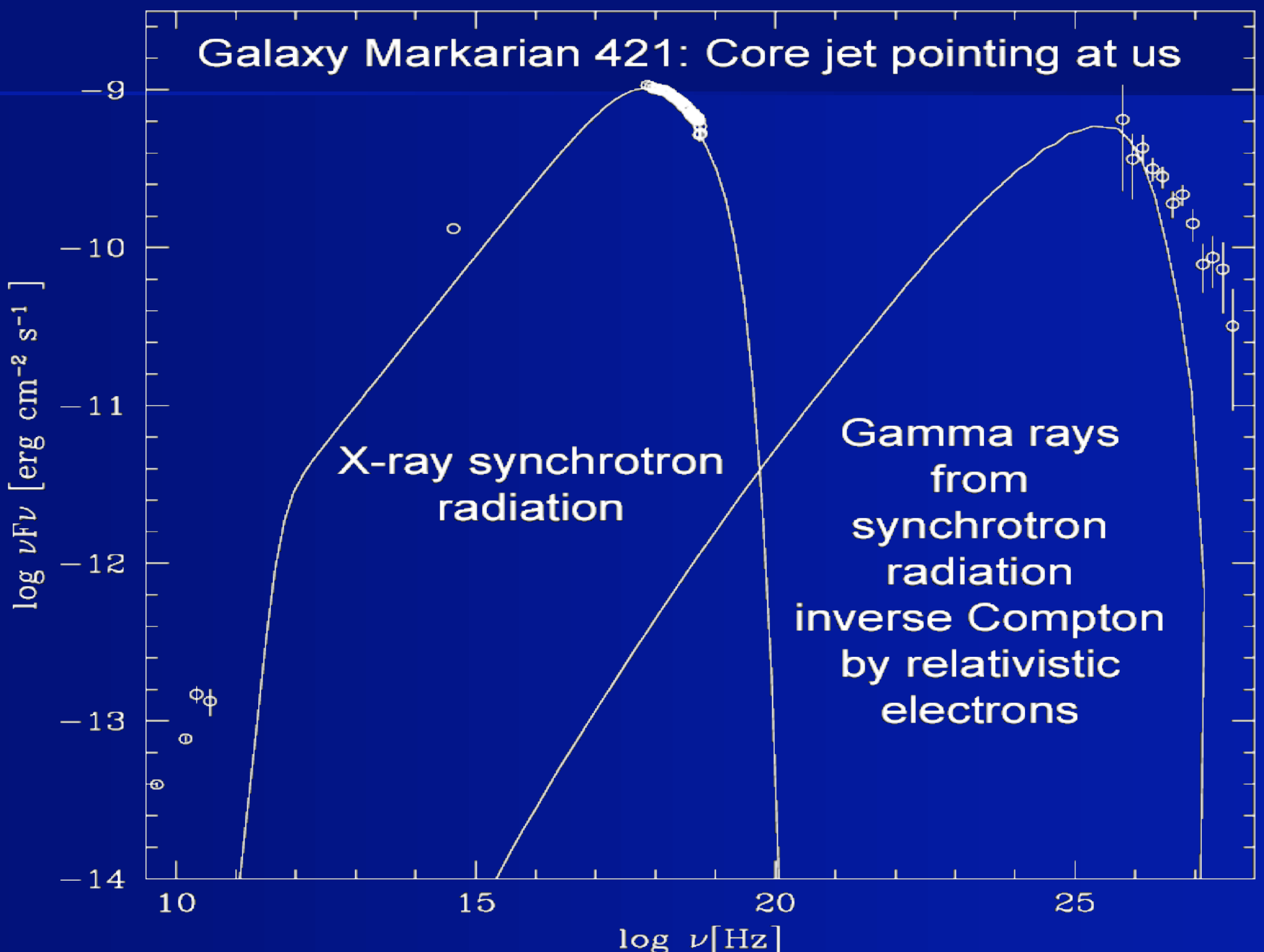
$$d\,P / d\Omega \, d\nu \; / \; \gamma^2 \, \nu \, \exp(- \nu / \nu_c)$$

$$\nu_c = (3 / 2) \, \gamma^2 \, \omega_L$$

Now integrate over angle and supposed electron density at each electron energy to get expected intensity per unit light frequency!

(General result in Jackson)

Synchrotron Radiation Theory IV



Plasma Physics near Compact Objects

- E & M (Maxwell)
- QED (Dirac)
- General Relativity (Einstein)

Relativistic Plasma Physics

X-Ray Radiation from Exotic Astrophysical Phenomena

Extreme Electric and Magnetic Fields: Magnetars

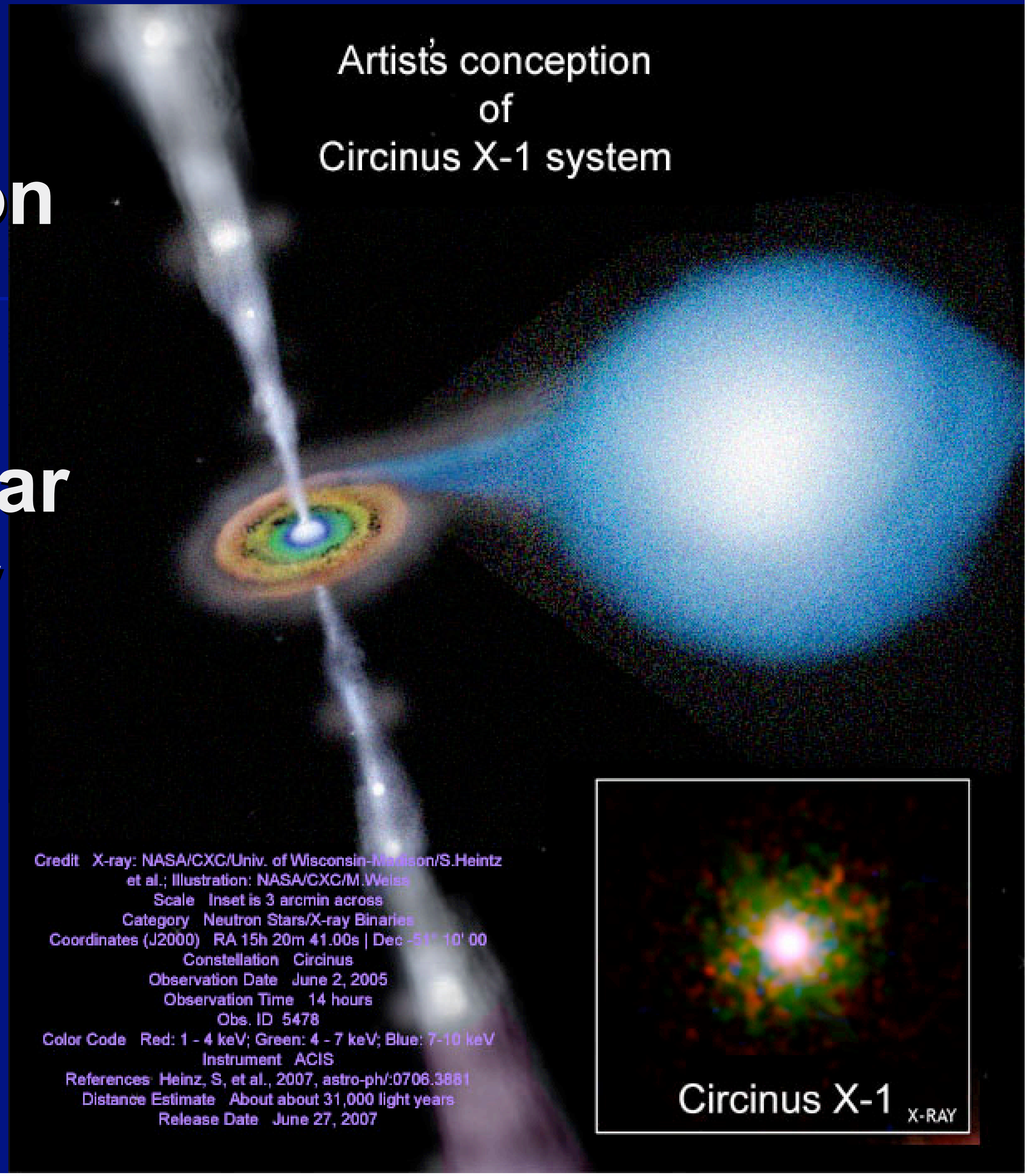
Extreme Gravitational Effects: Black Holes

High-Energy Radiation from Magnetic Compact Objects

- Thermal radiation from surface of compact object or hot plasma; bremsstrahlung radiation
- Radiation from star quakes and magnetic reconnections
- Radiation from infalling plasma
- Thermonuclear explosions from accreted matter
- Synchrotron radiation near a neutron star or black hole
- Inverse synchrotron radiation and e^+e^- cascading in jets
- Curvature radiation

Recent observation of jets from a neutron star in a binary system

(Report:
June 27, 2007)

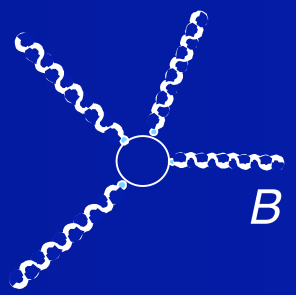


Magnetars

- Created by stellar collapse with quasi-magnetic flux conservation plus dynamo effect for fast rotation and high turbulence
- Cowling's Theorem (Dynamo effect requires asymmetry)
- 'Fast' spin-down due to magnetic field-crust interaction (Magnetic dipole radiation dominates spin energy loss in ordinary pulsars)
- Proton Landau transitions (Quantized orbits in B field)
- Strong Curvature Radiation (electrons radiate in direction of curving B)
- Atomic Orbit Distortion ('Cigar'-shaped orbitals)
- Photon splitting (QED: Photons connect to vacuum bubble)
- Pair Creation in strong B field
- Limits to E^2 and B^2 (B near proton, B near magnetar)

$$(P = - B^2 R^6 \Omega^4 \sin^2 \alpha / (6c^3))$$

$$\nu = \gamma^3 v / (2 \pi R_c)$$



Fields near a Magnetar

Neutron star acts as an almost perfect conducting sphere surrounded, to first approximation, by a magnetic dipole field:

$$B_r = 2\mu \cos\theta / r^3 \quad B_\theta = \mu \sin\theta / r^3 \qquad \mu = B_0 R^3$$

Charges on the rotating surface experience a Lorentz $q\,(\boldsymbol{v} / c) \times \boldsymbol{B}$.

The charges separate until the created electric force tangent to the surface cancels the tangential Lorentz force. The corresponding electric field will be

$$E_\theta = - \left(2\,\mu\,\Omega / (c\,R^2) \right) \sin\theta \cos\theta \qquad \text{(quadrupole)}$$

Using Gauss' law and that the tangential component of E must be continuous, there will be a radial component outside the star given by

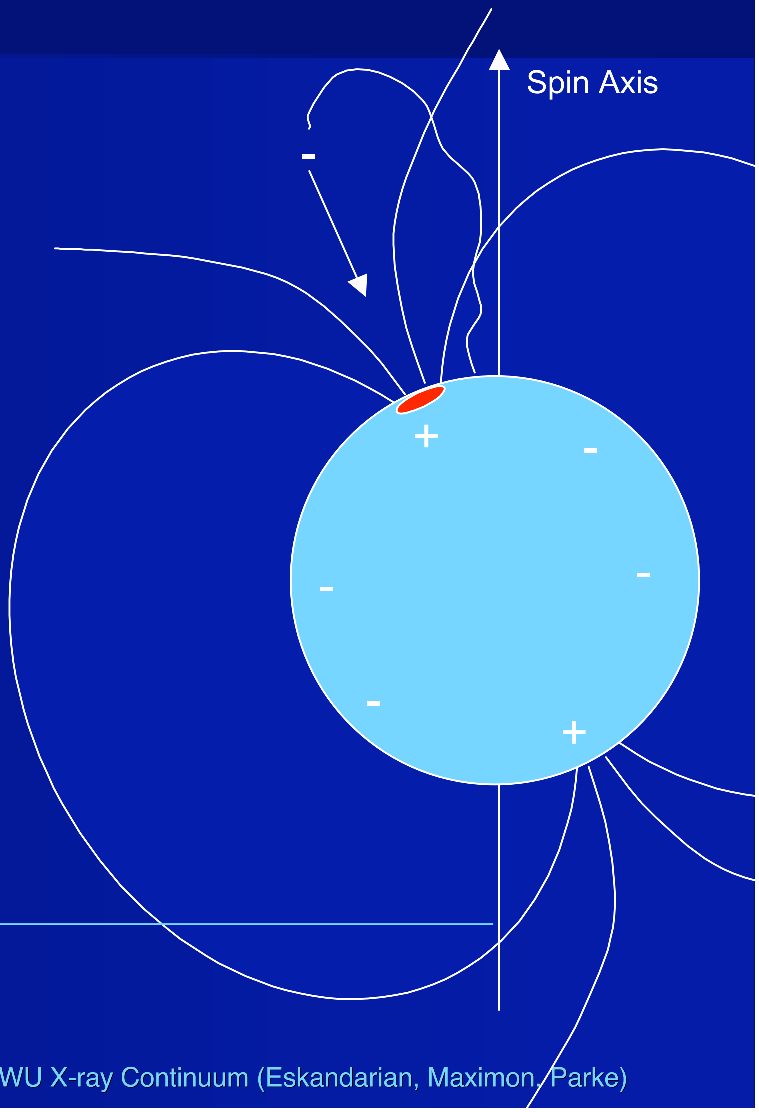
$$E_r = - (\mu\,\Omega\,R^2 / c) (3 \cos^2\theta - 1) / r^4 \qquad |\boldsymbol{E}\cdot\boldsymbol{B}| > 0 \text{ on surface}$$

Fields near a Magnetar II

The corresponding electric potential is

$$V = (\mu R^2 \Omega / (3c)) (3\cos^2\theta - 1) / r^3$$

Fields of the order of 10^{10} volts per centimeter are typical. Charges on the neutron star will be ripped from the surface, filling the magnetosphere with a plasma. An electric field in the plasma will accelerate the charges, creating plasma currents and trapping magnetic flux. The currents will intersect the magnetic poles.

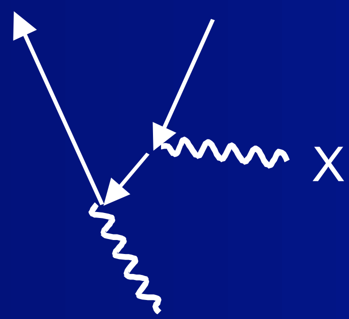


Radius of "light cylinder"

Critical Magnetic and Electric Fields

$B_Q = m_e^2 c^3 / (\hbar e)$ — 1.3×10^{16} V / cm; 4.3×10^{13} G — electron-pair creation

(Schwinger pair production)

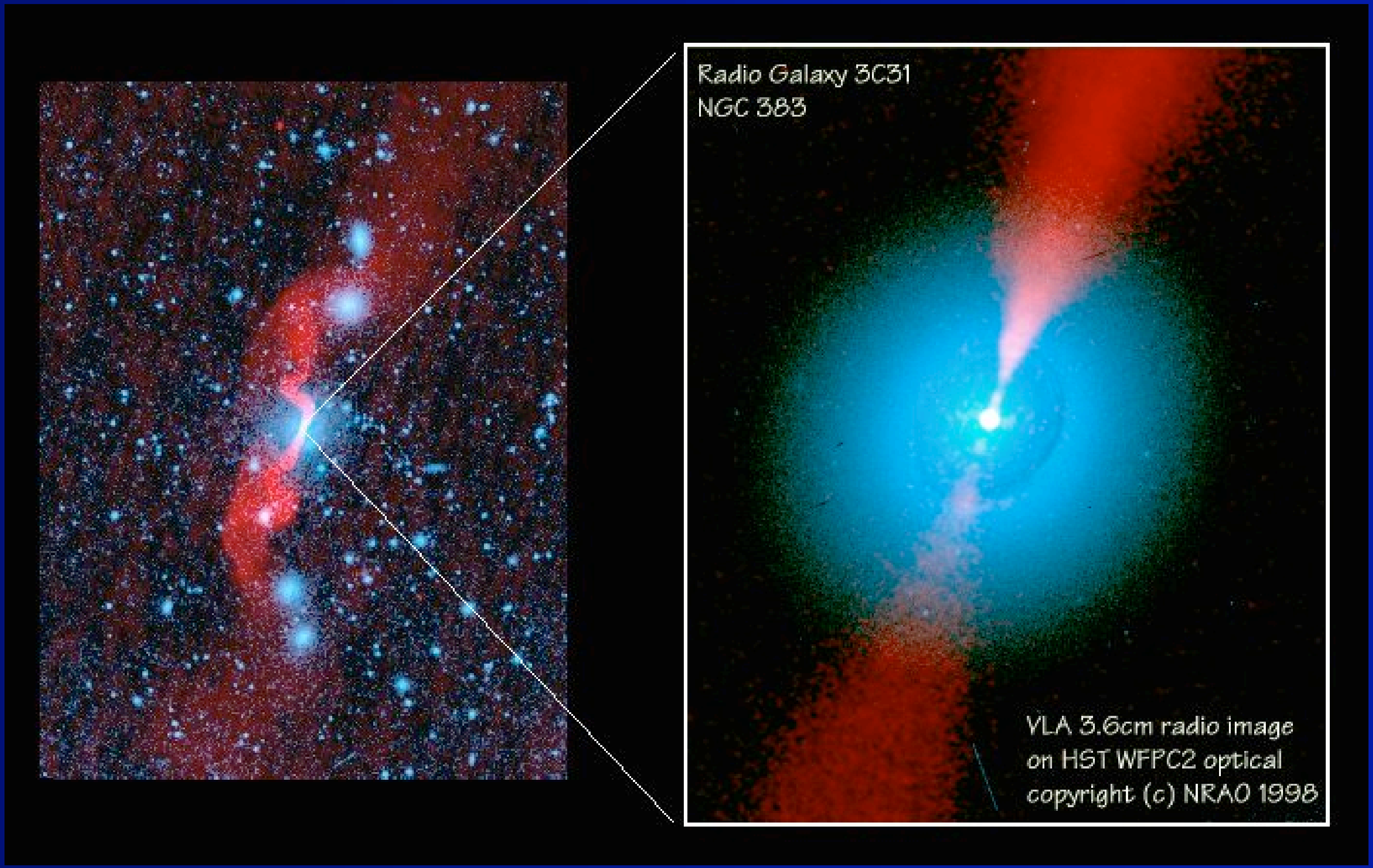


$B_M = m_m^2 c^3 / (\hbar e)$ — $>10^{18}$ G — monopole-pair creation

$B_G = \sqrt{c^7 / (h G^2)}$ — $\sim 10^{56}$ G — graviton creation

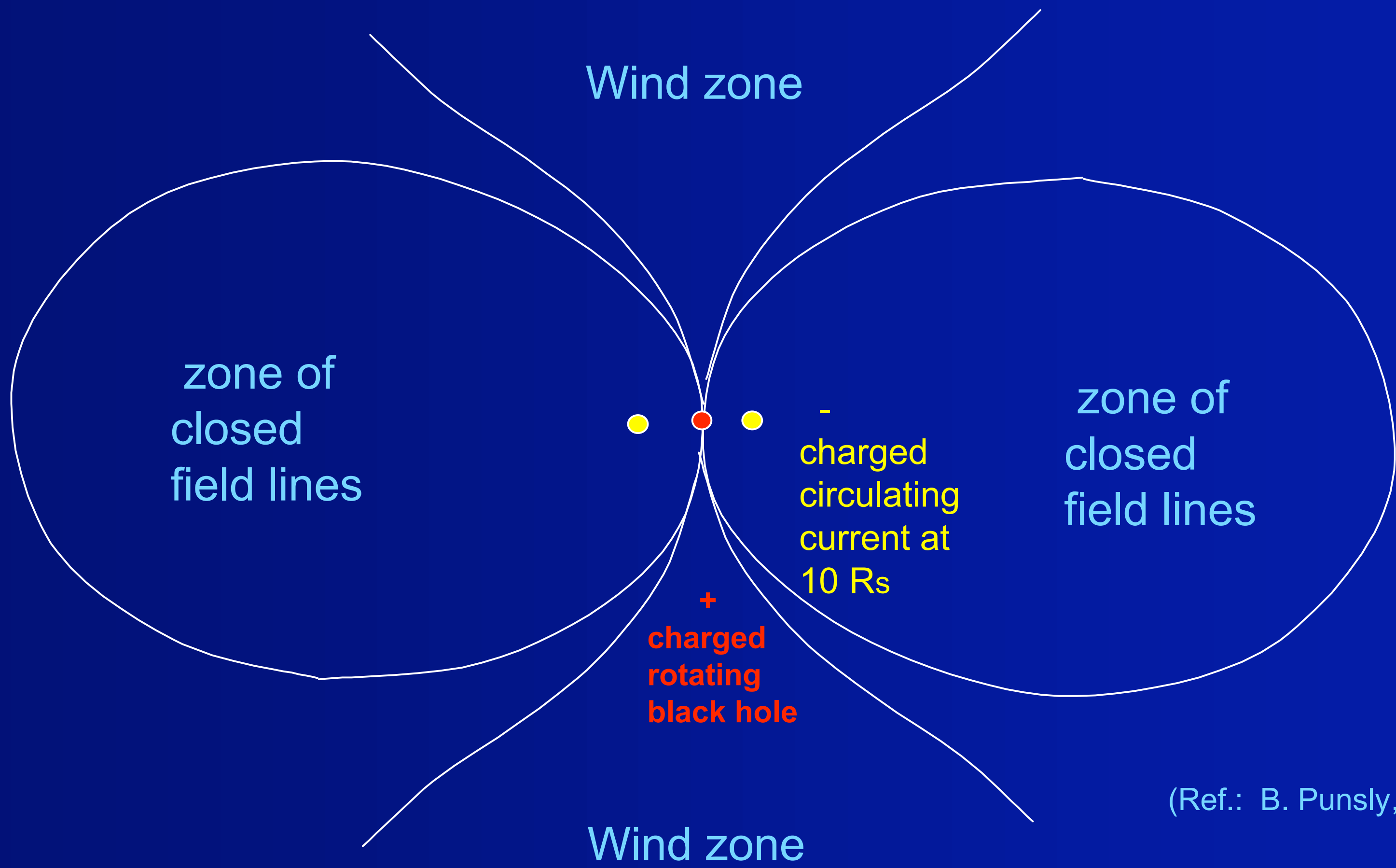
Black Holes

There are massive energetic compact objects at center of large galaxies



Black hole Gravitohydromagnetic object

Externally, similar to magnetar!

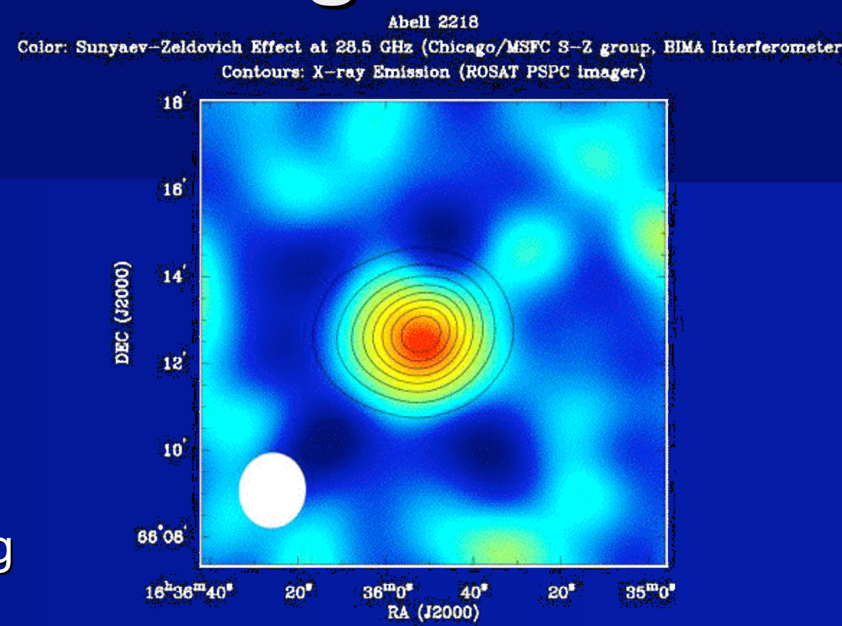


(Ref.: B. Punsly, 2001)

END

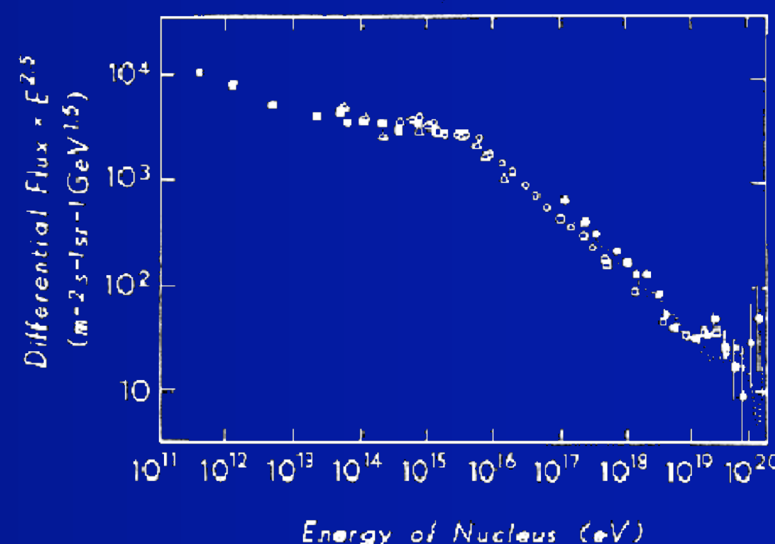
(Except for encore)

Cosmic Microwave Background Radiation Effects



The Sunyaev-Zel'dovich effect:

Frequency distribution of cosmic background photons shifts by scattering through plasmas near galactic clusters



Greisen-Zatsepin-Kuzmin effect:

Upper limit to cosmic ray energy due to scattering by CMBR

(Also limits space craft speeds !)